

Simple analytical solution and efficiency improvement of polysilicon emitter solar cells

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Abstract

A simple analytical model has been developed to simulate the performance of solar cells with polysilicon contact on the front surface. The polysilicon layer with a columnar grain structure is modeled by an effective recombination velocity using a two-dimensional transport equation. A one-dimensional transport equation in the single-crystal emitter is solved, taking into account bulk recombination and non-uniformly doped emitter. Then, simple analytical expressions for the emitter reverse saturation current and light-generated current densities are obtained. The collection of the light-generated carriers in polysilicon layer has been discussed and an analytical solution of the light-generated current is derived. The results show that the polysilicon layer can result in a decrease in emitter reverse saturation current density and an increase in solar cell photovoltaic parameters. In fact, the emitter region should not be treated as a 'dead layer' because thin polysilicon layer front surface contact gives an improvement of about 60 mV for the open-circuit voltage, 3.6 mA/cm² for the photocurrent, and 3.9% for the cell efficiency.

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1. Introduction

The introduction of heavily doped polycrystalline silicon for the emitter of bipolar transistor improves current gain by a factor of 3–30 compared to the conventional bipolar transistor [1–6]. Several theoretical models have been proposed in the literature and it has been established that this enhancement in current gain is due to the decrease in the emitter reverse saturation current. It is expected [3,4] that for the same reason the use of the polysilicon on the front surface of a silicon solar cell may enhance the photovoltaic parameters. Considerable amount of work has been reported on the polysilicon emitter solar cell. Green and Blakers [7] used the polysilicon contacts in MINP structure and reported enhancement in the open-circuit voltage. Subsequently, Garry Tarr [8] in 1985 fabricated solar cells with polysilicon on the top surface of the emitter. Photocurrent densities in excess of

30 mA cm^{−2} were obtained and an open-circuit voltage of 652 mV was achieved. Mehta [9] in 1986 presented an analysis of the decrease in the emitter reverse saturation current of a polysilicon emitter solar cell. He attributed this decrease to the transport in the polysilicon layer which assumes that polysilicon is formed by one grain characterized by some 'average' value of hole diffusion length and mobility. Papadopoulos et al. [10] obtained a fill factor close to 0.8 and achieved an open-circuit voltage of 665 mV. The solar cell, having 0.15 μm-thick emitter, gave a higher total-area efficiency. More recently, in their experimental studies, Castaner et al. [11] reported more enhancement in open-circuit voltage and short circuit current when the free oxidized surface at the polysilicon/silicon interface was passivated. Tilak and Bhat [12] showed that a better performance of polysilicon emitter solar cells can be achieved when the polysilicon layer thickness is about 0.2 μm.

Thus, even though considerable amount of theoretical work has been reported on the polysilicon emitter bipolar transistors and solar cells, most of these works are based on

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Nomenclature

q	electron charge
V_T	thermal voltage
$W_s(W_{sm})$	single-crystal emitter thickness for solar cell with (without) polysilicon contact
$W_b(W_{poly})$	base (polysilicon) thickness
d_g	grain width
δ	interfacial oxide thickness
ψ_s	interface potential barrier
N_e	emitter surface doping level
N_b	base doping level
$S_M(S_n)$	front (back) surface recombination velocity
$S_{is}(S_{ip})$	hole recombination velocity at single-crystal emitter (polysilicon) side
$T_{is}(T_{ip})$	interface blocking factor on the single-crystal (on the polysilicon) side
V_g	hole recombination velocity at the grain boundary
$S_{poly}(S_{mono})$	effective recombination velocity relative to the polysilicon (single-crystal emitter) region
$S_{peff}(S_{meff})$	effective recombination velocity at poly/mono-interface calculated from the single-crystal emitter (the polysilicon emitter)
$p_0(y)$	hole concentration at equilibrium
Δp_D	excess hole density at the dark in the polysilicon region
$J_{oEM}(J_{oEP})$	emitter reverse saturation current density for metal (polysilicon) contact emitter solar cell
J_{oB}	base reverse saturation current density solar cell
$J_{poly,D}$	injected current density at the dark in the polysilicon region

α	silicon absorption coefficient
Γ_o	photon flux density
V_{oc}	open-circuit voltage
$\eta(\%)$	conversion efficiency
$D_{p1}(L_{p1})$	hole diffusion coefficient (length) in the monocrystalline grain
$(D_{p2})\tau_{p2}$	hole diffusion coefficient (lifetime) in the single-crystal emitter region
$D_{eff}(\tau_{eff})$	average hole diffusion coefficient (lifetime) in the single-crystal emitter
L_{eff}	average hole diffusion length in the single-crystal emitter
Δp_L	light-generated excess hole density in the polysilicon
u_L	light-generated normalized excess hole density in the single-crystal emitter
$J_{pLE,P}$	light-generated hole current density in the total emitter region
$J_{pLE,poly}(J_{pLE,mono})$	light-generated hole current density in the polysilicon (single-crystal) emitter
$J_{pLE0,poly}$	light-generated hole current density in the polysilicon when $\Delta p_{L(at B)} = 0$
$J_{pLT,P}(J_{pLT,M})$	total light-generated current density for polysilicon (metal) contact emitter solar cell
ΔJ_{pLT}	increase in total light-generated current density
F_{p-o}	poly/oxide factor
P_{mP}	maximum output power of polysilicon emitter solar cell
$V_{mP}(J_{mP})$	voltage (current density) at maximum power output
P_{in}	incident power for 1 Sun AM1

simplified assumptions which may limit their applicability. In most cases, either the recombination in the single-crystal emitter is neglected [1,2,13] or a simplified model for the transport in the polysilicon is assumed, or the grain boundaries are considered to be parallel to the n–p junction [1–4,13–16].

The aim of this paper is to present a comprehensive analytical model to improve the photovoltaic parameters of solar cells with polysilicon contact on the front surface. The present analysis is based on the effective recombination velocity (ERV) method, and further extends and adjusts the works carried out in Refs. [14,16].

In the polysilicon region, the grain boundaries are taken perpendicular to the n–p junction solar cell. By using a two-dimensional transport equation, it is shown that the minority carrier injection in this region is simply described by an ERV. This approach allows for an accurate description of the complex minority-carrier transport in the polysilicon region, in the dark and under illumination, by a simple model.

The poly/mono-interface is described by the same expression of the ERV obtained in [16], including the

new expression of ERV established for polysilicon layer with columnar grain boundaries.

The minority-carrier transport in the non-uniformly and heavily doped single-crystal emitter is developed using the average value approach presented in Ref. [17] which gives more accurate results.

The increase in the photovoltaic solar cell parameters, due to polysilicon, is derived. The dependence of the emitter reverse saturation current density J_{oEP} , the light-generated current density $J_{pLT,P}$, the open-circuit voltage V_{oc} , and the conversion efficiency η on the cell parameters is discussed.

2. Theory

2.1. Emitter reverse saturation current density

A two-dimensional schematic diagram of the n⁺–p solar cell with a polysilicon emitter, including the physical and structural parameters and the doping profile are given in Fig. 1. Table 1 shows all the physical parameter values used.

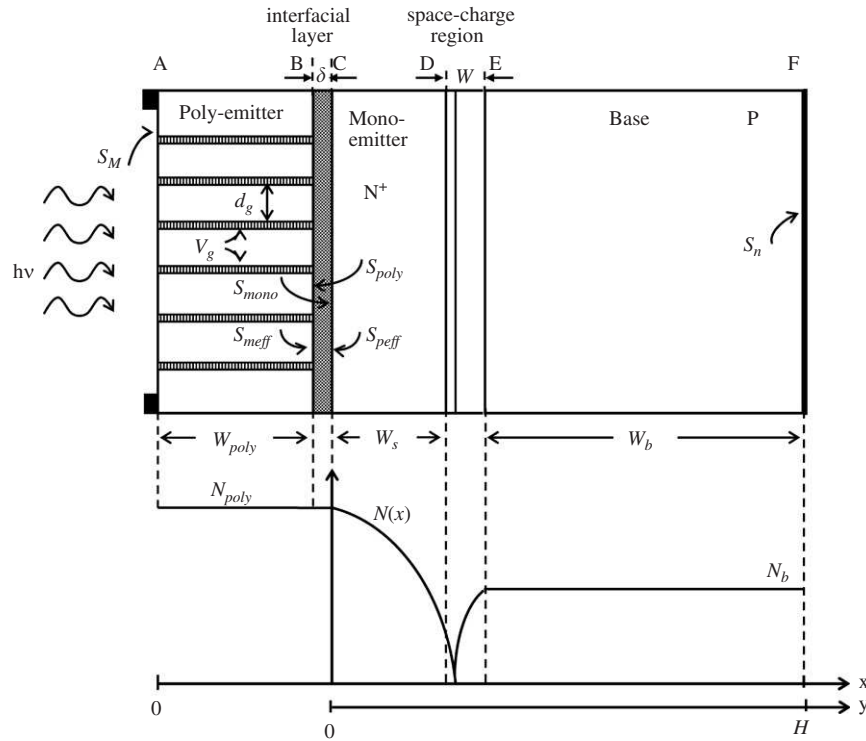


Fig. 1. Schematic diagram of a two-dimensional model of an $n^+ - p$ solar cell with polysilicon contact on the front surface, including various physical and structural parameter symbols.

Table 1
Physical parameter values

Parameter	Value	Ref.
W_{sm}	0.3 μm	
W_s	0.05 μm	
W_b	50 μm	
N_c	10^{19} cm^{-3}	
N_b	$6 \times 10^{16} \text{ cm}^{-3}$	
ψ_s	20 mV	[13]
S_M	$3.3 \times 10^6 \text{ cm s}^{-1}$	[16]
S_n	10^2 cm s^{-1}	
V_g	10^5 cm s^{-1}	
S_{is}	$1.6 \times 10^3 \text{ cm s}^{-1}$	[13]
S_{ip}	$1.6 \times 10^3 \text{ cm s}^{-1}$	[13]

The emitter consists of a polysilicon layer (AB), an interfacial oxide layer (BC), and a single-crystal silicon layer (CD). The holes are injected from the p-base over the junction, cross the segregation potential barrier on the single crystal side, and then tunneled through the interfacial oxide into the polysilicon region. The idea is to obtain the emitter reverse current density equal to hole current density injected into the emitter at D (at $x = W_{poly} + \delta + W_s$).

To do so, we modeled the polysilicon region and the poly/mono-interface by an ERV. Our model includes: non-uniform doping concentration in the single-crystal emitter (gaussian profile); diffusion, and recombination in the bulk of the crystal silicon region; tunneling through the native

oxide at the polysilicon/silicon interface; columnar grain orientation; diffusion and recombination in the bulk of the grains, and recombination at the grain/grain boundary interfaces.

2.1.1. Modeling of the polysilicon emitter

The polysilicon layer has a thickness W_{poly} , and is terminated by a metal contact (see Fig. 1). Recombination at the metal contact can be characterized by a recombination velocity S_M .

In most previous works [1–4,13,15], the polysilicon layer is assumed to be a simple region which is formed by one monocrystalline grain having average values of the hole diffusion length and mobility. In other works [14,16], the polysilicon layer is considered as a succession of grains limited by grain boundaries oriented parallel to the n–p junction, and is characterized by an ERV.

In our approach, we consider a columnar grain texture for the polysilicon emitter layer, in which the grain boundaries are oriented perpendicularly to the n–p junction (Fig. 1). Each grain is considered to be a single crystal silicon of width d_g . The grain boundary is assumed as a plan characterized by a recombination velocity V_g . Similarly to the previous texture [14,16], where the grain boundaries are oriented parallel to the n–p junction, the polysilicon layer can also be modeled by an ERV S_{poly} , which is calculated by solving the two-dimensional continuity equation and the current transport equation in grain volume.

The minority-carrier continuity equation in the n -type region is given by the following expression:

$$\frac{\partial^2 \Delta p_D}{\partial x^2} + \frac{\partial^2 \Delta p_D}{\partial z^2} - \frac{\Delta p_D}{L_{p1}^2} = 0, \quad (1)$$

where Δp_D is the excess hole density at the dark and L_{p1} the hole diffusion length.

The two boundary conditions in the x -direction are

$$\text{At } x = 0, \quad D_{p1} \left. \frac{\partial \Delta p_D}{\partial x} \right|_{x=0} = S_M \Delta p_D[x = 0; z], \quad (2)$$

$$\text{At } x = W_{\text{poly}}, \quad D_{p1} \left. \frac{\partial \Delta p_D}{\partial x} \right|_{x=W_{\text{poly}}} = S_{\text{poly}} \Delta p_D[x = W_{\text{poly}}; z]. \quad (3)$$

The two boundary conditions in the z -direction are

$$2D_{p1} \left. \frac{\partial \Delta p_D}{\partial z} \right|_{z=0} = +V_g \Delta p_D[x; z = 0], \quad (4)$$

$$2D_{p1} \left. \frac{\partial \Delta p_D}{\partial z} \right|_{z=d_g} = -V_g \Delta p_D[x; z = d_g], \quad (5)$$

where V_g is the recombination velocity at the grain boundary.

The injected current density in the polycrystalline emitter is given by

$$J_{\text{poly,D}} = q \frac{D_{p1}}{d_g} \int_0^{d_g} \left. \frac{\partial \Delta p_D(x, z)}{\partial x} \right|_{x=W_{\text{poly}}} dz. \quad (6)$$

So, the ERV S_{poly} , that thoroughly accounts for hole injection into the polysilicon, can be expressed as

$$S_{\text{poly}} = \frac{1}{d_g} \sum_{k \geq 0} \left\{ \frac{8 \sin^2(C_k d_g/2)}{C_k^2 d_g + C_k \sin(C_k d_g)} \right\} \times \left\{ \frac{\frac{D_{p1}}{L_k} \tanh\left(\frac{W_{\text{poly}}}{L_k}\right) + S_M}{1 + \frac{S_M L_k}{D_{p1}} \tanh\left(\frac{W_{\text{poly}}}{L_k}\right)} \right\}, \quad (7)$$

where $1/L_k^2 = C_k^2 + 1/L_{p1}^2$. C_k coefficients are the solutions of the transcendent equation:

$$\text{tg}\left(\frac{C_k d_g}{2}\right) = \frac{V_g}{2C_k D_{p1}}, \quad (8)$$

and D_{p1} is the hole diffusion coefficient in the monocrystalline grain.

2.1.2. Modeling of the interface

Due to the process of depositing polysilicon on the single-silicon emitter, an insulating layer is introduced between the polysilicon and silicon. Its thickness depends on chemical treatment prior to polysilicon deposition [5,18]. The holes are assumed to cross the potential barrier by thermionic emission, and then to tunnel through the oxide layer. The poly/mono-interface can be described by an ERV S_{peff} which accounts for hole transport across the interface, hole diffusion into the polysilicon, and surface

recombination given by [16]

$$S_{\text{peff}} = S_{\text{is}} + T_{\text{is}} \frac{S_{\text{poly}} + S_{\text{ip}}}{T_{\text{ip}} + S_{\text{poly}} + S_{\text{ip}}}, \quad (9)$$

where S_{ip} and S_{is} represent the interface recombination velocity at both sides of the interfacial oxide. T_{ip} and T_{is} represent ‘average’ velocity of the holes at the boundaries B and C, respectively, and depend on the physical mechanism controlling the hole flow at the interface. In our calculation T_{ip} and T_{is} are taken from the model of Ma et al. [13]. S_{poly} is the ERV given by Eq. (7) which characterizes the effect of the polysilicon layer on the behavior of the minority carriers in the crystalline emitter.

2.1.3. Modeling of the crystalline silicon emitter

In almost most of the previous polysilicon emitter models (bipolar transistor or solar cell) [1,2,13], the hole current density injected into the single-crystal emitter is calculated by neglecting bulk recombination (transparent emitter). This approximation is reasonable in metal contacted emitters, due to the high value of the contact recombination velocity S_M . The bulk recombination is then neglected with respect to the contact recombination current [19]. However, this approximation is invaluable for polysilicon emitter contact due to the much lower value of S_{peff} [20]. This has been demonstrated by the experimental results relative to devices with a deliberately grown interfacial oxide [18].

It has been shown that the emitter reverse saturation current density injected into a single-crystal emitter for any contact recombination velocity, S , may be accurately calculated by a simple approximate expression using the average value approach [17] which takes into account bulk recombination:

$$J_{\text{oE}} = qp_0(0) \frac{\left(\frac{D_{\text{eff}}}{L_{\text{eff}}}\right) \tanh\left(\frac{W_s}{L_{\text{eff}}}\right) + S}{1 + \left(\frac{SL_{\text{eff}}}{D_{\text{eff}}}\right) \tanh\left(\frac{W_s}{L_{\text{eff}}}\right)}, \quad (10)$$

where $\tau_{\text{eff}} = p_0(0)W_s / \int_0^{W_s} (p_0(y)/\tau_{p2}(y))dy$, $D_{\text{eff}} = W_s/p_0(0) / \int_0^{W_s} (dy/D_{p2}(y)p_0(y))$, $L_{\text{eff}} = \sqrt{D_{\text{eff}}\tau_{\text{eff}}}$ as defined in Ref. [17].

τ_{p2} and D_{p2} represent the hole lifetime and diffusion coefficient in the single-crystal region, respectively [21], while, τ_{eff} and D_{eff} represent their average value. L_{eff} is the average value of the diffusion length in the single crystal. $p_0(y)$ is the minority-hole concentration which takes account of the position-dependent doping and band-gap narrowing.

Replacing the contact recombination velocity S in Eq. (10) by S_{peff} (S_M), a general analytical formulation for emitter reverse saturation current, J_{oEP} (J_{oEM}), for polysilicon (metal) contacted devices is obtained.

2.2. Emitter light-generated current density

The light-generated hole current density, $J_{\text{PLE,P}}(\lambda)$, in the emitter consists of two contributions from the polysilicon

and the single-crystal regions. It can be written at $x = W_{\text{poly}} + \delta + W_s$ (at $x = D$) as

$$J_{\text{pLE,p}}(\lambda) = J_{\text{pLE,poly}}(\lambda) + J_{\text{pLE,mono}}(\lambda). \quad (11)$$

2.2.1. Single-crystal emitter light-generated current density

The current continuity equation for minority carriers, generated by a monochromatic light in the single-crystal emitter region, with an arbitrary doping profile and using our average value approach [17] is given as follows:

$$\frac{d^2 u_L(y)}{dy^2} - \frac{u_L(y)}{L_{\text{eff}}^2} = -\frac{1}{D_{\text{eff}}} g(y). \quad (12)$$

$u_L(y)$ is the light-generated normalized excess hole concentration. The term $g(y)$ is the generation rate of minority carriers (holes).

Using the following boundary conditions:

$$u_L = 0 \quad \text{at } y = D \quad (13)$$

$$D_{\text{eff}} \frac{du_L}{dx} = S_{\text{peff}} u_L \quad \text{at } y = C, \quad (14)$$

the solution of the current continuity equation (Eq. (12)) is given by

$$J_{\text{pLE,mono}} = \frac{q\Gamma_o \exp[-\alpha(W_{\text{poly}} + \delta)](1-R)\alpha L_{\text{eff}}}{(\alpha^2 L_{\text{eff}}^2 - 1)} \times \left\{ \begin{aligned} & \left(\frac{(\alpha L_{\text{eff}} + (S_{\text{peff}} L_{\text{eff}}/D_{\text{eff}})) - \exp(-\alpha W_s)}{\times [(S_{\text{peff}} L_{\text{eff}}/D_{\text{eff}}) \cosh(W_s/L_{\text{eff}}) + \sinh(W_s/L_{\text{eff}})]} \right) \\ & \frac{(S_{\text{peff}} L_{\text{eff}}/D_{\text{eff}}) \sinh(W_s/L_{\text{eff}}) + \cosh(W_s/L_{\text{eff}})}{\alpha L_{\text{eff}} \exp(-\alpha W_s)} \end{aligned} \right\}. \quad (15)$$

The ERV S_{peff} is calculated from Eq. (9).

2.2.2. Polysilicon emitter light-generated current density

The light-generated excess carriers in the polysilicon region must be collected at the poly/oxide interface (at $x = B$) cross the segregation potential barrier ψ_s and tunnel through the interfacial oxide to enter the bulk. Then the carriers diffuse across the entire single-crystal emitter region to reach the junction. Only the carriers surviving recombination can contribute to the short-circuit current.

We are now considering the poly/oxide interface property. Holes are minority carriers on both side of poly/oxide interface. They may cross the interfacial layer and reach the single-crystal emitter. If $\Delta p_{\text{L(at B)}}(\lambda)$ represents the light-generated excess hole concentration at $x = B$, then the boundary conditions in the x -direction can be written as

$$D_{\text{p1}} \frac{\partial \Delta p_{\text{L}}}{\partial x} \Big|_{x=0} = S_{\text{M}} \Delta p_{\text{L}}[x; z] \quad \text{at } x = A, \quad (16)$$

$$\Delta p_{\text{L}}[x; z] = \Delta p_{\text{L(at B)}} \quad \text{at } x = B. \quad (17)$$

The two boundary conditions in the z -direction are the same as those given by Eqs. (4) and (5).

The solution of the two-dimensional current continuity equation subject to the above boundary conditions is given, at B by:

$$J_{\text{pLE,poly(at B)}}(\lambda) = \frac{q}{d_g} \sum_{k \geq 0} \frac{\Gamma_o(1-R)\alpha L_k}{(\alpha^2 L_k^2 - 1)} \left[\frac{8 \sin^2(C_k d_g/2)}{C_k^2 d_g + C_k \sin(C_k d_g)} \right] \times \left\{ \begin{aligned} & \left(\frac{((S_{\text{M}} L_k/D_{\text{p1}}) + \alpha L_k) - \exp(-\alpha W_{\text{poly}})}{\times [(S_{\text{M}} L_k/D_{\text{p1}}) \cosh(W_{\text{poly}}/L_k) + \sinh(W_{\text{poly}}/L_k)]} \right) \\ & \frac{(S_{\text{M}} L_k/D_{\text{p1}}) \sinh(W_{\text{poly}}/L_k) + \cosh(W_{\text{poly}}/L_k)}{-\alpha L_k \exp(-\alpha W_{\text{poly}})} \end{aligned} \right\} - \frac{q}{d_g} \sum_{k \geq 0} \left\{ \frac{8 \sin^2(C_k d_g/2)}{C_k^2 d_g + C_k \sin(C_k d_g)} \right\} \times \left\{ \frac{(D_{\text{p1}}/L_k) \tanh(W_{\text{poly}}/L_k) + S_{\text{M}}}{1 + (S_{\text{M}} L_k/D_{\text{p1}}) \tanh(W_{\text{poly}}/L_k)} \right\} \Delta p_{\text{L(at B)}}. \quad (18)$$

Eq. (18) can be written as

$$J_{\text{pLE,poly(at B)}} = J_{\text{pLE0,poly}} - q S_{\text{poly}} \Delta p_{\text{L(at B)}}, \quad (19)$$

where $J_{\text{pLE0,poly}}$ is the hole light-generated current density in the polysilicon region collected at the polysilicon/oxide interface ($x = B$) when $\Delta p_{\text{L(at B)}} = 0$, and S_{poly} is the ERV given by Eq. (7). The value of $J_{\text{pLE,poly(at B)}}$ can be obtained if $\Delta p_{\text{L(at B)}}$ is known. For the boundary condition at $x = B$, we also have

$$J_{\text{pLE,poly(at B)}} = q S_{\text{meff}} \Delta p_{\text{L(at B)}}. \quad (20)$$

Substituting Eq. (20) into (19) gives

$$\Delta p_{\text{L(at B)}} = \frac{J_{\text{pLE0,poly}}}{q(S_{\text{poly}} + S_{\text{meff}})}. \quad (21)$$

By combining Eqs. (20) and (21), we can rewrite $J_{\text{pLE,poly(at B)}}$ in a more explicit form as

$$J_{\text{pLE,poly(at B)}} = \frac{J_{\text{pLE0,poly}}}{1 + S_{\text{poly}}/S_{\text{meff}}}. \quad (22)$$

The physical meaning of the ERV S_{meff} is that it accounts for the effects of the single-crystal emitter on the minority carriers of the polysilicon region. Therefore, referring to Eq. (9), S_{meff} is simply obtained as

$$S_{\text{meff}} = S_{\text{ip}} + T_{\text{ip}} \frac{S_{\text{mono}} + S_{\text{is}}}{T_{\text{is}} + S_{\text{mono}} + S_{\text{is}}}. \quad (23)$$

To determine the ERV of the single-crystal emitter, S_{mono} , we concentrate on the surface at $x = D$. Note that the light-generated excess hole density $\Delta p_{\text{L(at D)}}$ is zero, since there is the equivalent of an infinite effective surface recombination

velocity at $x = D$. Therefore, referring to the expression (14) of Ref. [22] and using the average value approach, S_{mono} , is simply obtained as

$$S_{\text{mono}} = \frac{D_{\text{eff}}}{p_0(0)L_{\text{eff}}} \coth\left(\frac{W_s}{L_{\text{eff}}}\right). \quad (24)$$

Next, we should consider the recombination and tunnel losses crossing the interfacial layer. Current continuity at the poly/mono interface yields

$$J_{\text{pLE,poly(at B)}} = J_{\text{pLE,poly(at C)}} + qS_{\text{ip}} \Delta p_{\text{L(at B)}} + qS_{\text{is}} \Delta p_{\text{L(at C)}}. \quad (25)$$

Using the light-generated excess hole concentration ratio across the interface given by Ref. [16],

$$\beta = \frac{\Delta p_{\text{L(at C)}}}{\Delta p_{\text{L(at B)}}} = \frac{T_{\text{ip}}}{T_{\text{is}} + S_{\text{is}} + S_{\text{mono}}}, \quad (26)$$

the hole current collected at the oxide/silicon interface ($x = C$) is obtained as

$$J_{\text{pLE,poly(at C)}} = J_{\text{pLE0,poly}} F_{\text{p-o}}, \quad (27)$$

where $F_{\text{p-o}}$ is the poly-oxide factor given by

$$F_{\text{p-o}} = \frac{S_{\text{meff}} - (S_{\text{ip}} + \beta S_{\text{is}})}{S_{\text{meff}} + S_{\text{poly}}}. \quad (28)$$

Therefore, a general equation for the light current collected at the oxide/silicon interface is then expressed simply as the current $J_{\text{pLE0,poly}}$ reduced by $F_{\text{p-o}}$. The expression (Eq. (27)) is similar to the one established by Dai et al. for the light current collected by the high-low $n^+ - n$ junction front-surface-field (FSF) solar cell [22].

Substituting Eqs. (23) and (26) into (28) results in

$$F_{\text{p-o}} = \frac{1}{1 + \frac{S_{\text{is}} T_{\text{ip}} + (S_{\text{poly}} + S_{\text{ip}})(T_{\text{is}} + S_{\text{is}} + S_{\text{mono}})}{S_{\text{mono}} T_{\text{ip}}}}. \quad (29)$$

This shown that the poly-oxide factor, $F_{\text{p-o}}$, is a function of device parameters and is easy to determine when the parameters are provided.

Finally, we should consider the recombination loss in the single-crystal region. The hole current $J_{\text{pLE,poly}}$ collected at the depletion region $x = D$ is easily derived as

$$J_{\text{pLE,poly}} = J_{\text{pLE0,poly}} F_{\text{p-o}} \text{sech}\left(\frac{W_s}{L_{\text{eff}}}\right). \quad (30)$$

Eq. (30) gives the final expression of the contribution of light-generated hole current in the polysilicon region.

2.3. Photovoltaic parameters

The light-generated hole current density, $J_{\text{pLT,P}}$ in the polysilicon emitter solar cell is the result of contributions from three regions: the emitter region (polysilicon and single-crystal region), the base region, and the space charge region.

The increase in the light-generated hole current is given by

$$\Delta J_{\text{pLT}} = J_{\text{pLT,P}} - J_{\text{pLT,M}}, \quad (31)$$

where $J_{\text{pLT,M}}$ is the light-generated hole current density in a solar cell without polysilicon layer.

The expressions of the open-circuit voltage, with and without polysilicon layer solar cell, are given, respectively, by

$$V_{\text{ocP}} \approx V_T \ln\left(\frac{J_{\text{pLT,P}}}{J_{\text{oEP}} + J_{\text{oB}}}\right), \quad (32a)$$

and

$$V_{\text{ocM}} \approx V_T \ln\left(\frac{J_{\text{pLT,M}}}{J_{\text{oEM}} + J_{\text{oB}}}\right) \quad (32b)$$

The increase in open-circuit voltage is

$$\Delta V_{\text{oc}} = V_{\text{ocP}} - V_{\text{ocM}} \approx V_T \ln\left[\left(1 + \frac{\Delta J_{\text{pLT}}}{J_{\text{pLT,M}}}\right) \left(\frac{1 + (J_{\text{oEM}}/J_{\text{oB}})}{1 + (J_{\text{oEP}}/J_{\text{oB}})}\right)\right]. \quad (33)$$

We consider three cases of Eq. (33):

- (a) when the base reverse saturation current density is greater than the emitter reverse saturation current density, for both metal and polysilicon contact emitter solar cells ($J_{\text{oB}} \gg J_{\text{oEM}}$ and J_{oEP}), Eq. (33) becomes

$$\Delta V_{\text{oc}} \approx V_T \ln\left(1 + \frac{\Delta J_{\text{pLT}}}{J_{\text{pLT,M}}}\right). \quad (34)$$

- (b) when $J_{\text{oB}} \ll J_{\text{oEM}}$ and J_{oEP} , Eq. (33) will be

$$\Delta V_{\text{oc}} \approx V_T \ln\left[\frac{J_{\text{oEM}}}{J_{\text{oEP}}} \left(1 + \frac{\Delta J_{\text{pLT}}}{J_{\text{pLT,M}}}\right)\right] \quad (35)$$

- (c) when $J_{\text{oB}} \ll J_{\text{oEM}}$ but $J_{\text{oB}} \gg J_{\text{oEP}}$, Eq. (33) gives

$$\Delta V_{\text{oc}} \approx V_T \ln\left[\frac{J_{\text{oEM}}}{J_{\text{oB}}} \left(1 + \frac{\Delta J_{\text{pLT}}}{J_{\text{pLT,M}}}\right)\right]. \quad (36)$$

The maximum output power, per unit area, that can be obtained from the cell is given by

$$P_{\text{mP}} = V_{\text{mP}} J_{\text{mP}}. \quad (37a)$$

Here V_{mP} and J_{mP} are obtained from the following equations [23]:

$$\left(1 + \frac{V_{\text{mP}}}{V_T}\right) \exp\left(\frac{V_{\text{mP}}}{V_T}\right) = 1 + \frac{J_{\text{pLT,P}}}{(J_{\text{oEP}} + J_{\text{oB}})}. \quad (37b)$$

$$J_{\text{mP}} = \frac{V_{\text{mP}}(J_{\text{oEP}} + J_{\text{oB}})}{V_T} \exp\left(\frac{V_{\text{mP}}}{V_T}\right). \quad (37c)$$

The increase in maximum output power is

$$\Delta P = P_{\text{mP}} - P_{\text{mM}}. \quad (37d)$$

The increase in conversion efficiency for 1 Sun AM1 is then:

$$\Delta\eta(\%) = \eta_P(\%) - \eta_M(\%) = \frac{\Delta P}{P_{in}} 100, \quad (38)$$

where P_{in} the incident power for 1 Sun AM1 ($P_{in} = 0.1 \text{ W cm}^{-2}$).

3. Results and discussion

3.1. Effect of the polysilicon layer on the emitter reverse saturation current density of polysilicon emitter solar cells

In Section 2.1.3, an expression for the emitter reverse saturation current density, J_{oEP} , with polysilicon layer on the front surface of an n^+p silicon solar cell, using the average value approach and an ERV method, is derived. Fig. 2 shows the variation of J_{oEP} versus polysilicon thickness W_{poly} for different grain widths d_g and for devices without a deliberately grown interfacial oxide layer ($\delta = 3 \text{ \AA}$).

It may be noted that, for $d_g = 0.01 \text{ }\mu\text{m}$, J_{oEP} for devices having polysilicon thickness greater than about $0.05 \text{ }\mu\text{m}$ is almost constant, due to the large recombination at the grain boundary. However, when the poly thickness is reduced below the hole diffusion-length in the polysilicon region ($L_{(k=1)} = 0.06 \text{ }\mu\text{m}$ for $d_g = 0.01 \text{ }\mu\text{m}$), the current increases as poly thickness is reduced below $\sim 0.05 \text{ }\mu\text{m}$. When the grain width, d_g , is more than $0.01 \text{ }\mu\text{m}$, the recombination at the grain boundaries is less important and the minority carrier holes can reach the surface of the poly and get recombined, thereby increasing the J_{oEP} value with decreased poly thickness. This is consistent with the experimental results shown in Refs. [12,24]. It is interesting to note that the emitter reverse saturation current density, for devices without polysilicon layer, i.e. $W_{poly} = 0$ (J_{oEM}), is

lower than the one having a thin polysilicon layer ($W_{poly} = 0.005 \text{ }\mu\text{m}$) over the substrate for all grain width. This can be attributed to the fact that the emitter Gummel number in the former case is larger due to deeper junction compared to that in the latter where the junction depths are much shallower ($W_s = 0.05 \text{ }\mu\text{m}$ and $W_{sm} = 0.3 \text{ }\mu\text{m}$) Refs. [24,25]. The same experimental shape is observed in [12,24]. For devices with a deliberately grown interfacial oxide layer ($\delta = 14 \text{ \AA}$ [5]), the hole reverse current decreases importantly but becomes insensitive to polysilicon property (poly thickness, grain width, grain boundary recombination velocity,...). It can be deduced that the thickness of the interfacial oxide layer is an important parameter that controls the hole current.

3.2. Effect of the polysilicon layer on the photovoltaic parameters of polysilicon emitter solar cells

Fig. 3 shows the variation in the total light-generated current density of an n^+p solar cell with polysilicon contact on the front surface as a function of poly thickness for different grain widths. It can be noted that, for a thin deposited polysilicon layer ($W_{poly} = 0.005 \text{ }\mu\text{m}$), the total light-generated current increases and takes a maximum value ($\Delta J_{pLT} = 3.6 \text{ mA/cm}^2$ which corresponds to an increase of $\sim 11\%$ in J_{pLT}). This improvement is due to three reasons. Firstly, it results from the reduced thickness of the single-crystal emitter (i.e., the junction depth) which consequently enhances the contribution of short-wavelength light to the total light-generated current since, with a shallow emitter, the short-wavelength light would also be absorbed in the base where the generated carriers are collected more efficiently [26]. Secondly, it also results from the contribution of the polysilicon layer to the total light-generated carriers. Finally, it also results from the reduced

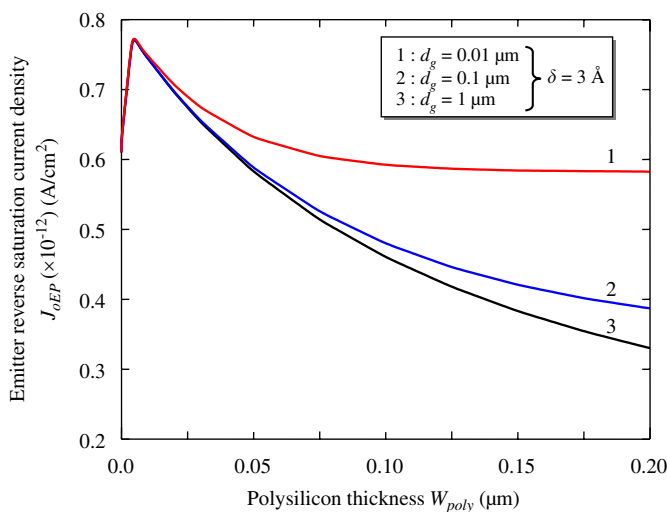


Fig. 2. Reverse saturation current density for polysilicon emitter solar cells versus polysilicon layer thickness for different grain width and for devices without deliberately grown interfacial oxide ($\delta = 3 \text{ \AA}$).

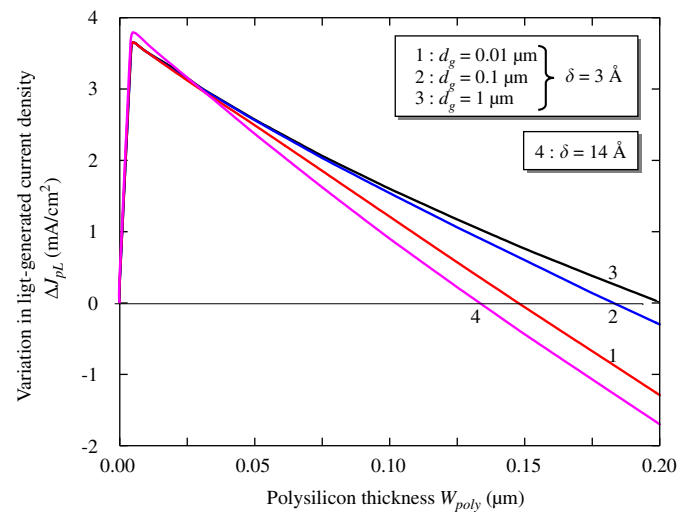


Fig. 3. Variation in the increase in light-generated current density for polysilicon emitter solar cells versus polysilicon layer thickness for different grain widths and for devices with and without deliberately grown interfacial oxide.

loss of light-generated carriers at the single-crystal emitter surface. However, this improvement decreases with increased poly thickness from $0.005\text{ }\mu\text{m}$ due to the absorption of the short-wavelength light in the polysilicon front region. For a given poly thickness, this improvement in total light-generated current decreases with (1) the decrease of the grain width due to the large recombination of the light-generated carriers at the grain boundaries, and with (2) the increase of interfacial tunnel oxide which prevents the light-generated holes in the polysilicon region to join the junction (at D). This loss can be minimized by taking the minimum polysilicon thickness with large grain width, and the suitable chemical treatment prior to polysilicon deposition which can offer the necessary decrease in the reverse saturation current (and consequently an improvement in photovoltaic parameters).

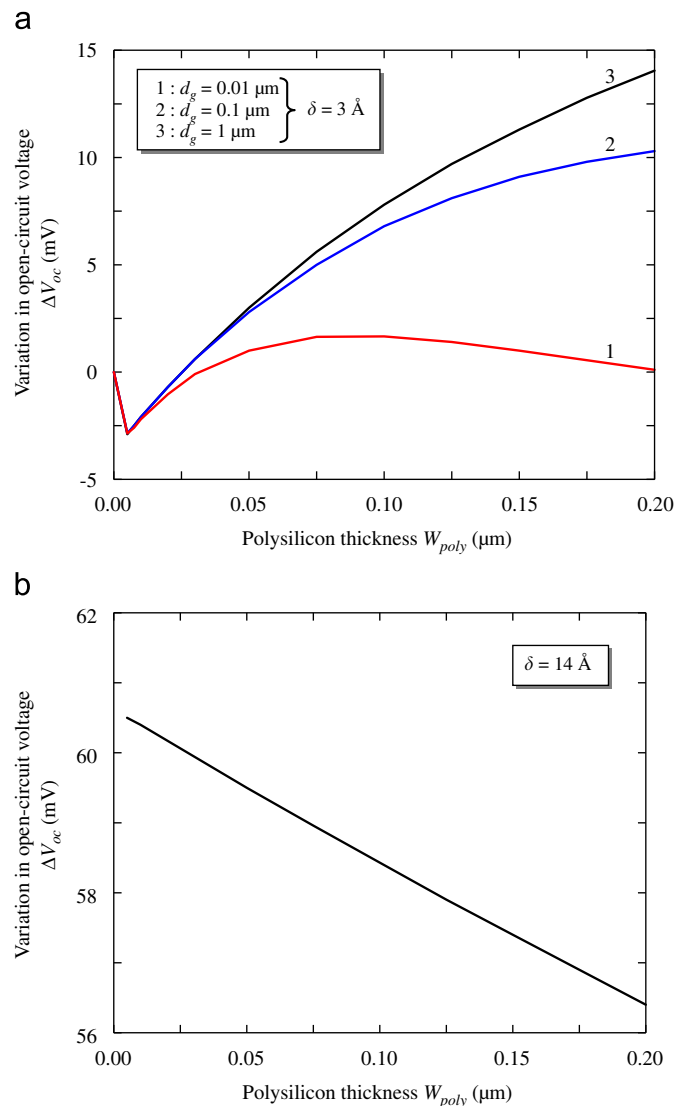


Fig. 4. Variation in the increase in open-circuit voltage for polysilicon emitter solar cells versus polysilicon layer thickness for different grain widths and for (a) devices without deliberately grown interfacial oxide ($\delta = 3\text{ }\text{\AA}$). (b) devices with deliberately grown interfacial oxide ($\delta = 14\text{ }\text{\AA}$). The grain width does not have any effect on open-circuit voltage.

The expression for the increase in open-circuit voltage ΔV_{oc} is given in Section 2.3 by Eq. (33). For lower doping base levels (higher substrate resistivity), the emitter reverse saturation current densities J_{oEM} and J_{oEP} are much smaller than those of the base J_{oB} even though the back surface is passivated. Consequently, ΔV_{oc} can be obtained by the approximate expression given by Eq. (34). In this case, the increase in V_{oc} is obtained from the increase in light-generated current density. This increase is quite small ($\Delta V_{oc} \sim 2.5\text{ mV}$) for a maximum expected increase of 7% in $J_{pL,P}$ ($\Delta J_{pLT}/J_{pL,M} = 7\%$). For higher doping base levels (lower substrate resistivity) and passivated back surface, the emitter reverse saturation current density is much larger than that of the base ($J_{oEM} \gg J_{oB}$).

When $J_{oEP} \gg J_{oB}$ (for devices without deliberately grown interfacial oxide), the increase in open-circuit voltage ΔV_{oc}

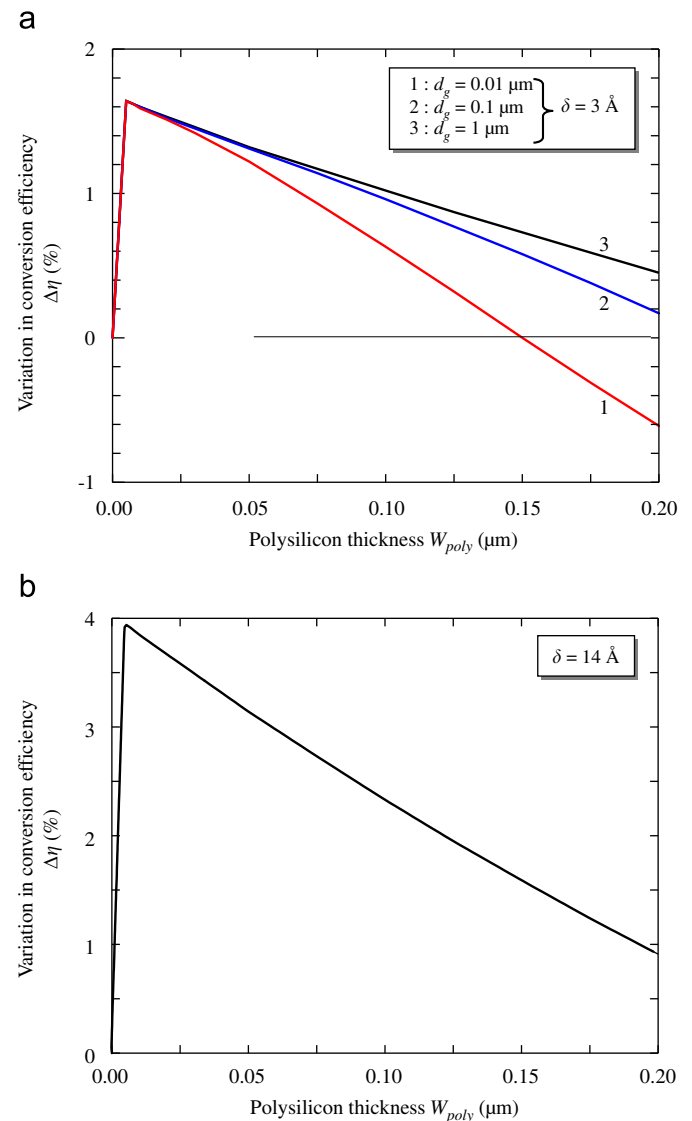


Fig. 5. Variation in the increase in conversion efficiency for polysilicon emitter solar cells versus polysilicon layer thickness for different grain widths and for (a) devices without deliberately grown interfacial oxide ($\delta = 3\text{ }\text{\AA}$). (b) devices with deliberately grown interfacial oxide ($\delta = 14\text{ }\text{\AA}$). The grain width does not have any effect on conversion efficiency.

can be obtained by Eq. (35). In this case, an increase in V_{oc} is governed by the decrease in J_{oEP} which depends, as is shown in Fig. 2, on polysilicon thickness, grain width, and interfacial oxide thickness.

Fig. 4(a) shows the variation of the increase in the open-circuit voltage ΔV_{oc} , calculated from Eq. (33), as a function of poly thickness for different grain widths and for devices with higher doping-level ($N_b = 610^{16} \text{ cm}^{-3}$) and without a deliberately grown interfacial oxide layer ($\delta = 3 \text{ \AA}$). It can be seen that the improvement in open-circuit voltage increases by increasing poly thickness and/or grain widths, which allows to decrease J_{oEP} [see Fig. 2] and ΔJ_{PLT} (see Fig. 3). This confirms that the decrease in J_{oEP} essentially accounts for the increase observed in ΔV_{oc} .

When $J_{oEP} \ll J_{oB}$ (for devices with deliberately grown interfacial oxide), the increase in open-circuit voltage ΔV_{oc} can be obtained by Eq. (36). In this case, greater improvements in V_{oc} can be achieved from polysilicon contact solar cell.

Fig. 4(b) shows the variation of the increase in the open-circuit voltage ΔV_{oc} , calculated from Eq. (33), as a function of poly thickness and for devices with higher doping-level ($N_b = 610^{16} \text{ cm}^{-3}$) and deliberately grown interfacial oxide layer ($\delta = 14 \text{ \AA}$). As is expected from Eq. (36), a very large improvement in open-circuit voltage is shown ($\Delta V_{oc} \sim 60 \text{ mV}$ for thin polysilicon layer). The slight decrease observed in open-circuit voltage with increasing poly thickness is essentially due to the decrease in light-generated current (see Fig. 3).

The variation in conversion efficiency are calculated from Eq. (38), and are plotted against poly thickness as shown in Figs (5a) and (b). The enhancement of efficiency with poly thickness for thin interfacial oxide follows a trend similar to that of the light-generated current. A great enhancement is observed for thin polysilicon layer; this enhancement decreases with poly thickness and grain widths.

Greater improvements in efficiency can be achieved from the polysilicon contact solar cell in devices with a

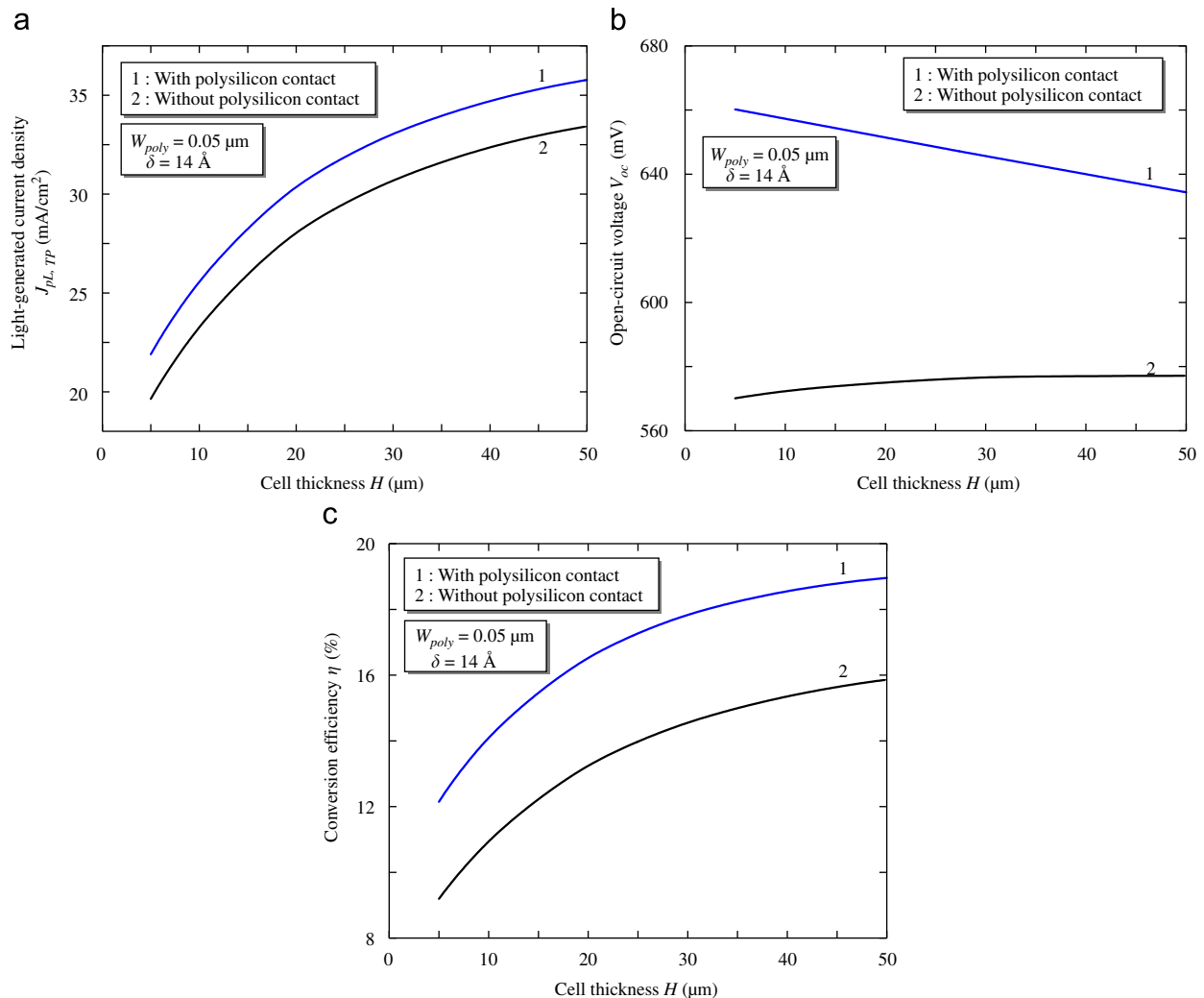


Fig. 6. Variation in (a) light-generated current density; (b) open-circuit voltage; (c) conversion efficiency versus cell thickness for: 1. cells with polysilicon contact on the front surface and 2. cells without polysilicon contact on the front surface. The polysilicon thickness $W_{poly} = 0.05 \mu\text{m}$ and the interfacial oxide $\delta = 14 \text{ \AA}$.

deliberately grown interfacial oxide with thin polysilicon layer whatever the grain widths are (see Fig. 5(b)).

Figs. 6(a–c) show the effect of base thickness on the cell parameters for solar cells with and without polysilicon contact on the front surface. The base-doping level varies with the base thickness; it is chosen to give a maximum efficiency. A conservative value for the back-surface velocity of 10^2 cm s^{-1} is considered. It is clear that the polysilicon contact on the front surface improves the cell parameters ($J_{\text{pL,T}}$, V_{oc} and η) significantly whatever the base thickness is. Thus, from these results, the emitter region should not be regarded as a ‘dead layer’ because the thin polysilicon layer front surface contact can result in an increase in open-circuit voltage, light-generated current, and conversion efficiency.

4. Conclusion

In this paper, an analytical model to simulate the performance of solar cells with polysilicon contact on the front surface has been developed. The polysilicon layer is considered to consist of a columnar grain structure and is modeled by an ERV using a two-dimensional transport equation. The transport equation in the single-crystal emitter is solved using the average value approach taking into account the bulk recombination and the non-uniformly doped emitter. Then simple analytical expressions for the emitter reverse saturation current and light-generated current densities are obtained. The collection of the light-generated carriers in the polysilicon layer has been discussed and the analytical solution for the contribution of the light-generated current from the polysilicon contact emitter is derived. From our model calculation, it may be concluded that the polysilicon layer with the native interfacial oxide at the front surface can, in effect, passivate the front surface, which result in a decrease in emitter reverse saturation current density. In addition, the deposited polysilicon layer can improve the light-generated current due to: the reduced thickness of the junction depth; the light-generated carriers within polysilicon layer; and the reduced loss of light-generated carriers to the single-crystal emitter surface.

Greater improvements in open-circuit voltage and efficiency can be achieved from polysilicon contact solar cells in devices with a deliberately grown interfacial oxide

with thin polysilicon layer whatever the grain width and cell thickness. From the established results, the emitter region should not be treated as a ‘dead layer’ because the thin polysilicon layer front surface contact solar cell show about 60 mV increase in open-circuit voltage, $\sim 3.6 \text{ mA cm}^{-2}$ improvement in light-generated current, and $\sim 3.9\%$ increase in absolute cell efficiency compared to conventional solar cells.

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